Probing the End of Helium Reionization at $z \sim 2.7$ with He II Lyman Alpha Absorption Spectra

Gábor Worseck (IMPS @ UCO/Lick)

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J. X. Prochaska (IMPS @ UCO/Lick), M. McQuinn (UCB), A. Dall'Aglio (AIP),
C. Fechner (UP), J. F. Hennawi (MPIA), P. Richter (UP),
D. Reimers (Hamburg), L. Wisotzki (AIP)

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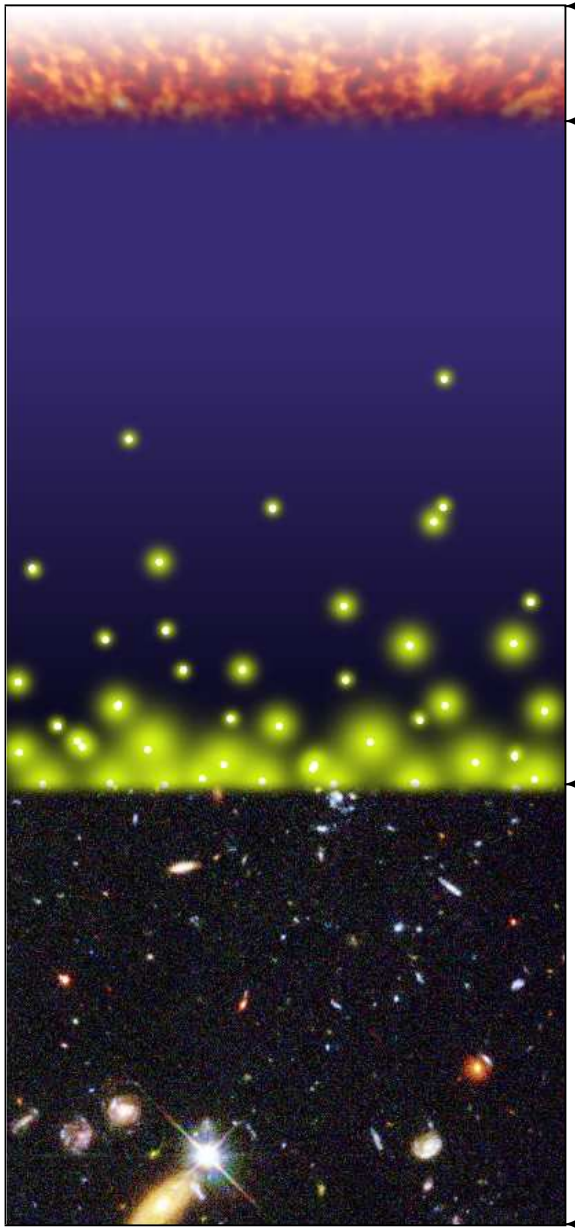
Outline

A short history of the universe



adapted from Djorgovski et al. & Digital Media Center, Caltech

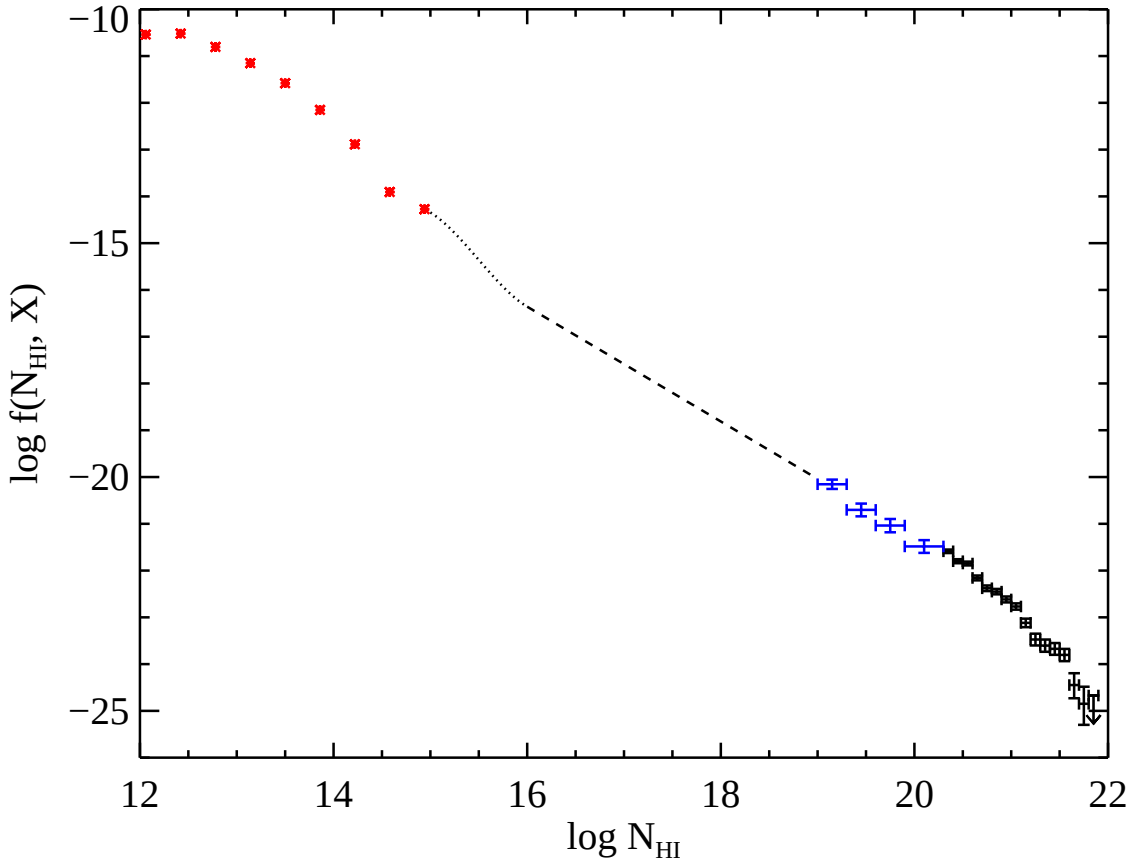
The basics of IGM absorption

credits: Andrew Pontzen

H I absorbers: Sinks & diffuse sources of UV radiation

- balance between photoionization and radiative recombination
- frequency distribution of $N_{\rm HI}$ values for IGM absorbers ('clouds')
- $\log N_{\rm HI} < 14.5$: optically thin Lyα forest
- $\log N_{\rm HI} > 20.3$: optically thick damped systems

- $17.2 < \log N_{\rm HI} < 20.3$: Lyman limit systems identified by Lyman limit break ($\tau_{912} > 1$), translucent at high energies
- $14.5 < \log N_{\rm HI} < 17.2$: translucent near the Lyman limit break

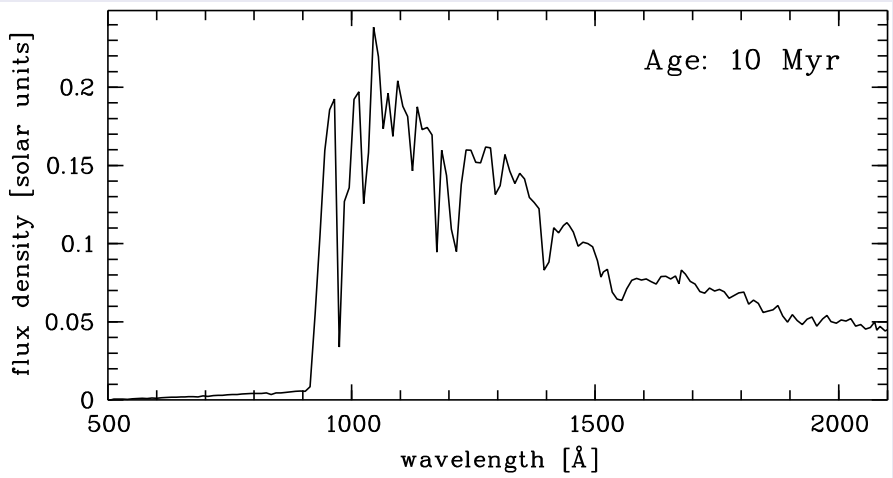


Prochaska & Tumlinson (2009)

Sources of the UV background

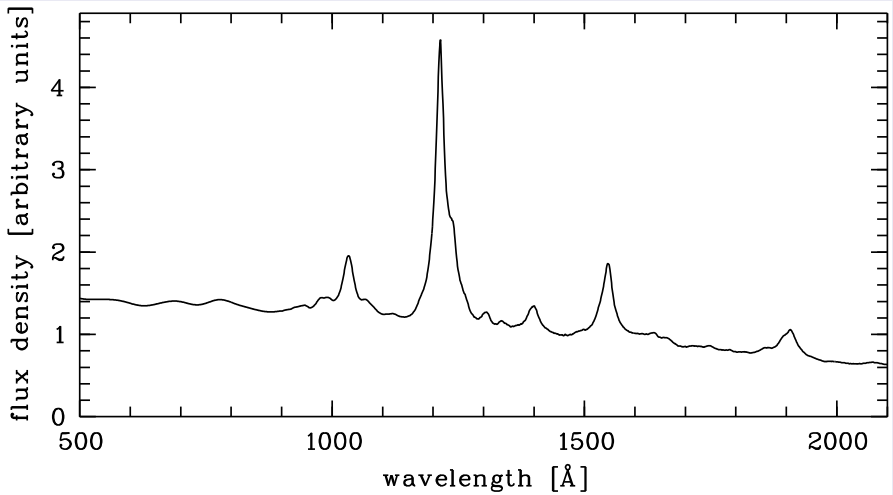
Star-forming galaxies

- high space density
- small escape fraction
- soft UV radiation



Quasars

- low space density
- short lifetime ($\sim$ 10 Myr)
- hard UV radiation

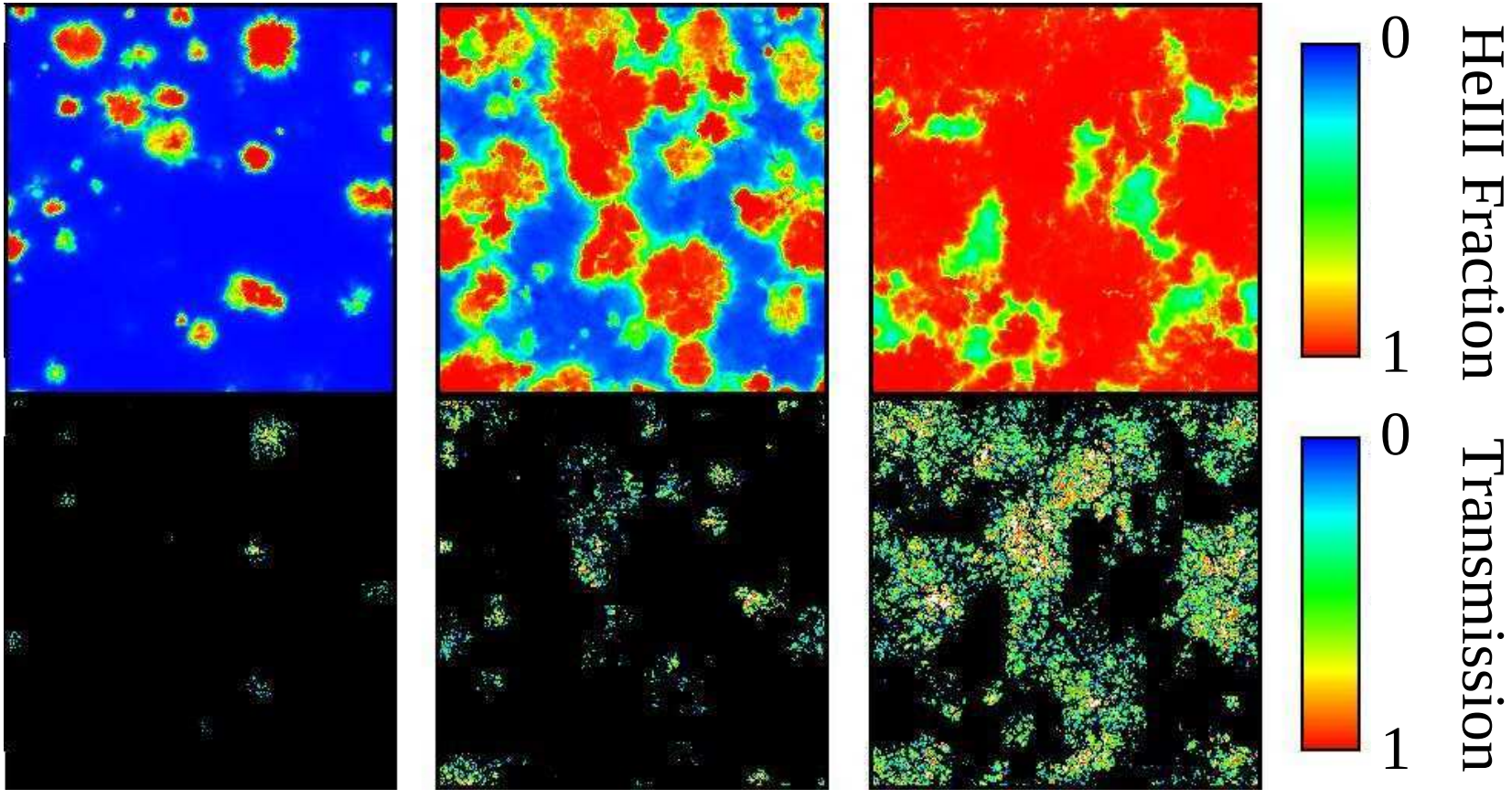


Overview: Intergalactic helium

- after reionization: IGM of H and He in photoionization equilibrium with UV background
- He reionization likely two-step process:
  1. He I $\longrightarrow$ He II @ $z \sim 6$ ($h\nu > 24.6$ eV required)
  2. He II $\longrightarrow$ He III @ $z \sim 3$ ($h\nu > 54.4$ eV required)
- reason: hard UV photons only produced by quasars, full He reionization delayed until quasars sufficiently abundant
- Tracers of He II reionization:
  - indirect: IGM temperature, ionization state of IGM metals
  - direct: He II Lyα absorption at $\lambda_{\rm rest} = 303.78$ Å (He II is hydrogenic ion)

Simulations: He III bubbles around quasars

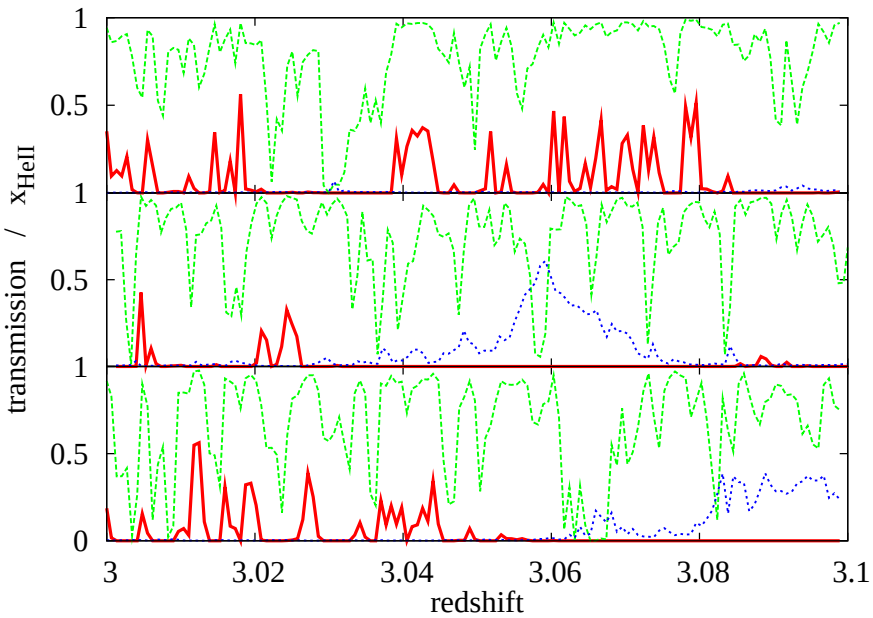
- semi-analytic models and radiative transfer simulations
- prediction: inhomogeneous and extended He II reionization ($\sim$ 1Gyr)

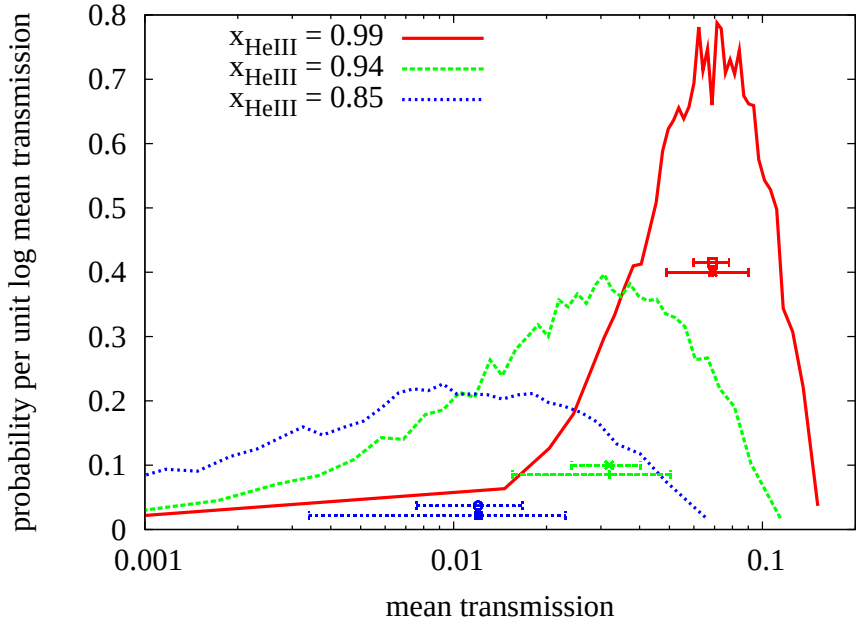


McQuinn et al. (2009)

Constraining He II reionization requires large samples

- large sightline variance in He II absorption, no impact on H I forest
- reason: stochasticity of He II-ionizing quasars
- $\gtrsim 25$ He II sightlines can distinguish simple reionization models

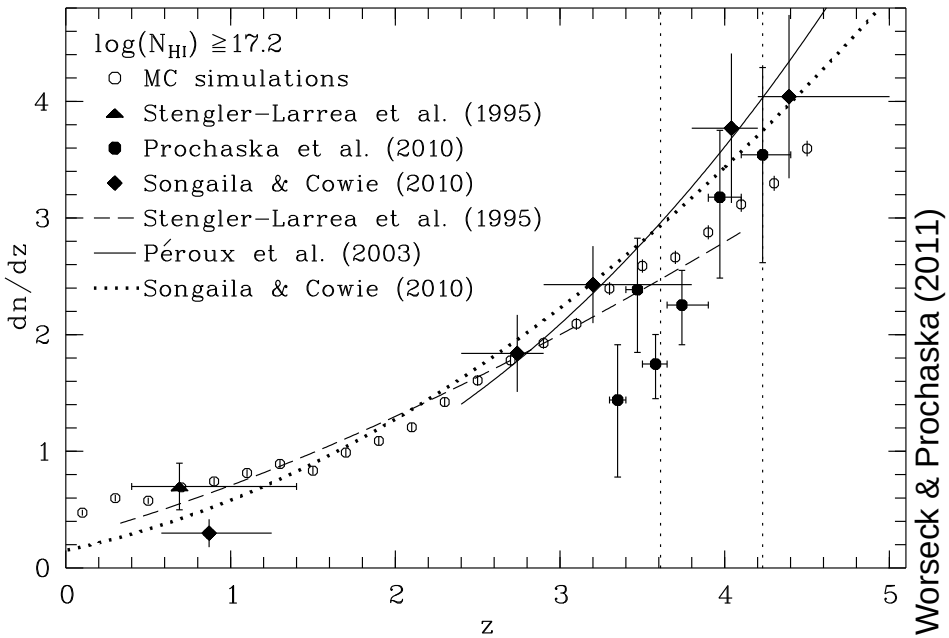


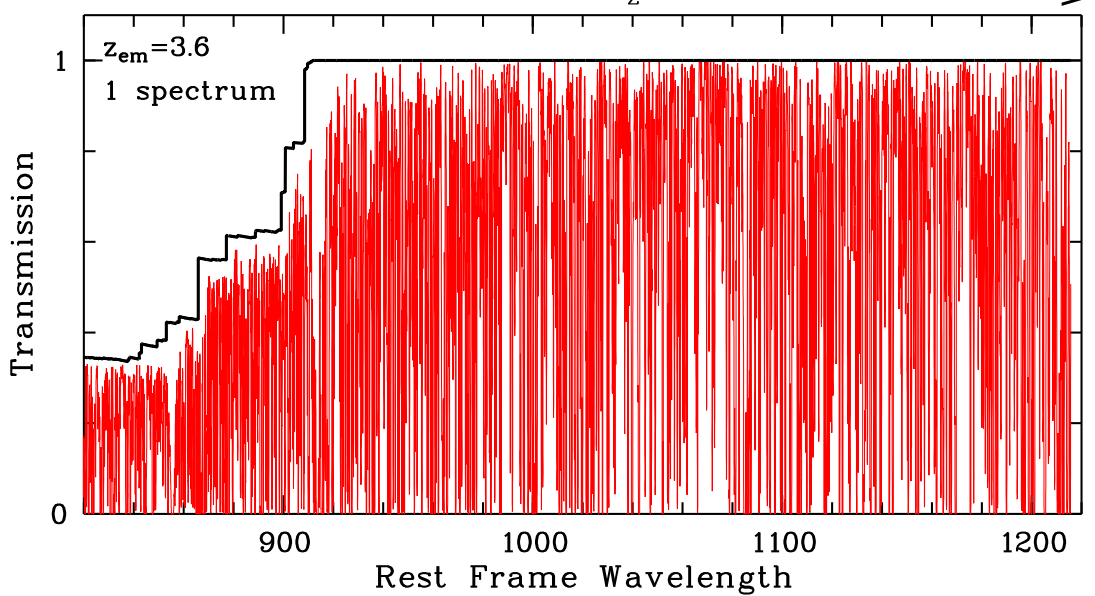


McQuinn et al. (2009)

Problem I: Far UV $\longrightarrow$ Lyman continuum absorption

- far UV transition $\longrightarrow$ space
- Galactic Lyman limit restricts He II observations to $z > 2$
- high-z Lyman limit systems $\longrightarrow$ strong cumulative Lyman continuum absorption
- $<$ 10% of all sightlines transparent at $\lambda_{\rm rest} = 304$Å



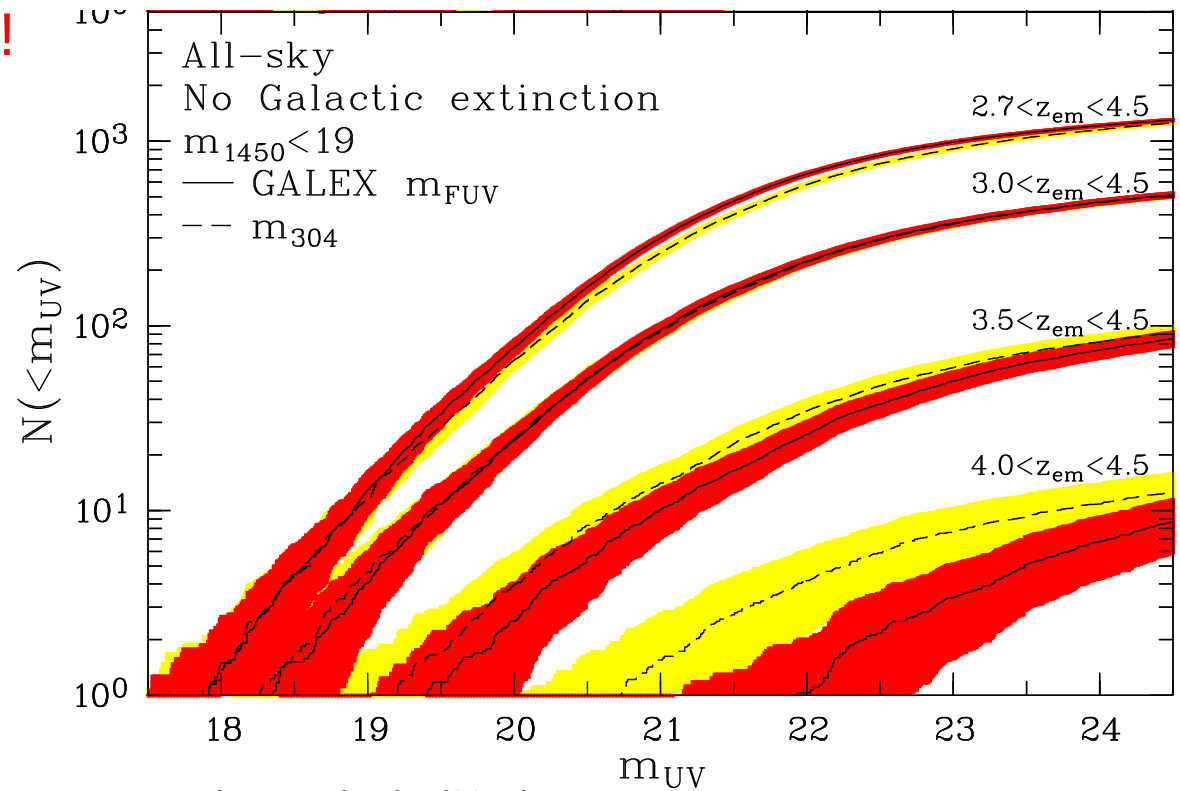


Problem II: UV-bright quasars are rare!

- IGM absorption + QSO LF = number of UV-bright QSOs
- most UV-bright quasars at low redshifts for He II studies ($z_{\rm em} < 3$)
- HST sensitivity limit: $z_{304} \gtrsim 2.7$
- prediction: ~ 200 $m_{304} < 21$ He II quasars

$\longrightarrow$HST probes He II reion.!

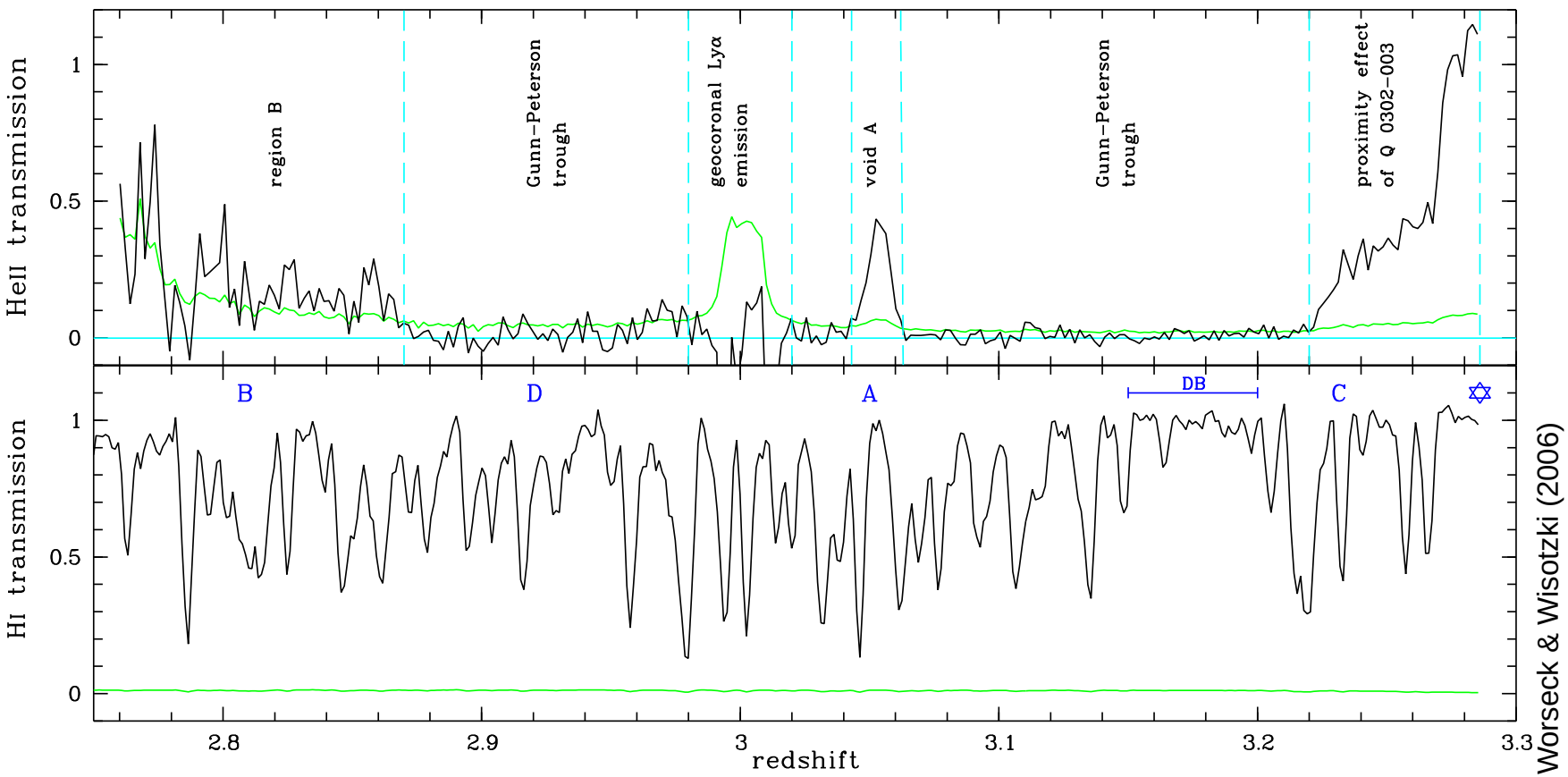
- assumption: unbiased '3π' quasar survey at $m_{1450} < 19$



Worseck & Prochaska (2011)

Few He II observations to date $\longrightarrow z_{\rm reion} \sim 3$

- only 5 sightlines studied at $R > 800$ (HST/STIS, FUSE)
- main features: Gunn-Peterson trough at $z > 3$, patchy He II absorption at $2.7 < z < 3$, forest at $z < 2.7$
- He III zones around background and foreground quasars



Selection of UV-bright QSOs from GALEX photometry

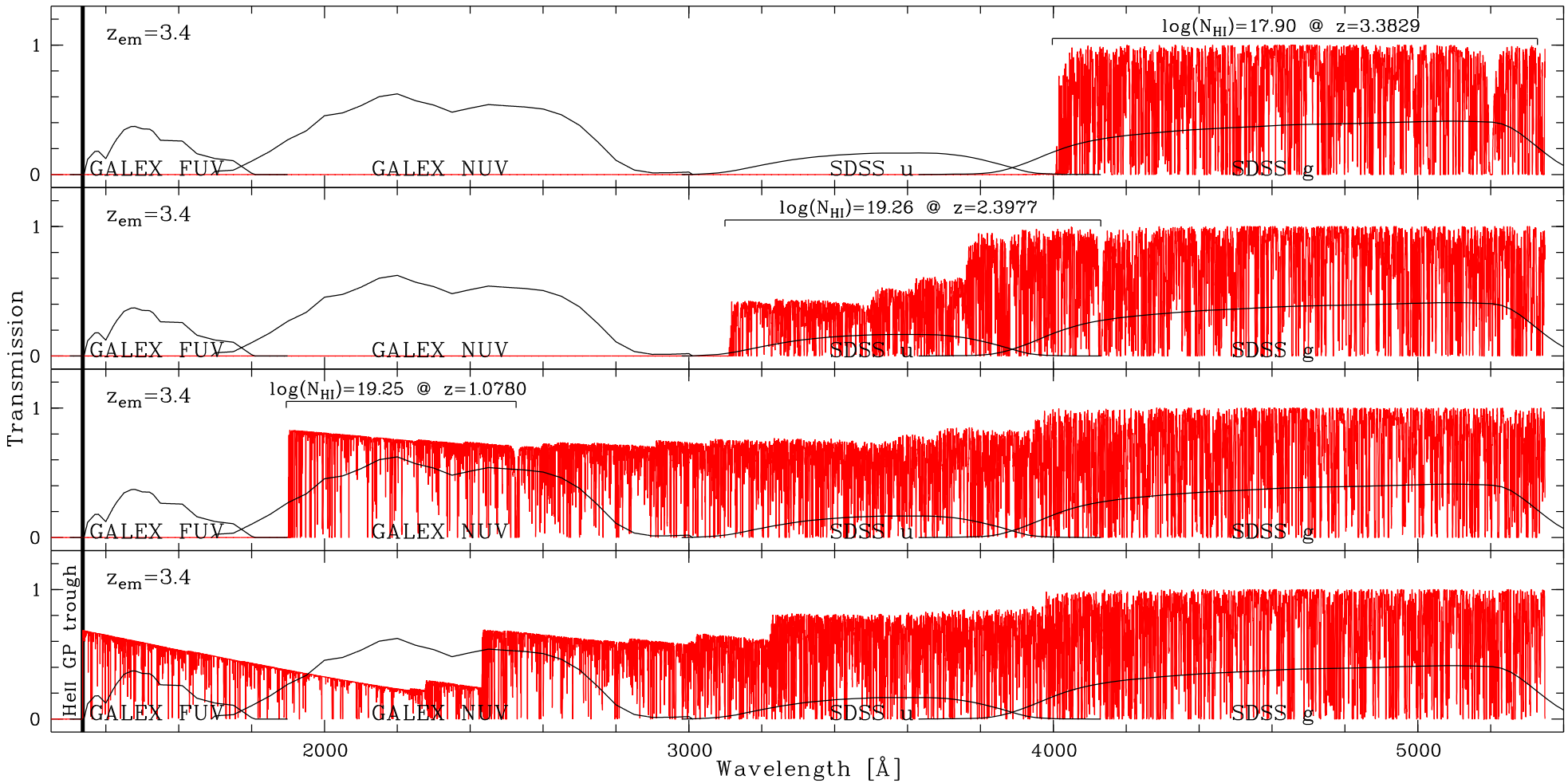
- previous surveys were UV-blind
- GALEX: first UV all-sky survey at $m_{AB} \lesssim 21$
- two bands: NUV (1750–2200Å) and FUV (1350-1750Å)

Follow-up of GALEX-detected high-z quasars

NASA/JPL-Caltech

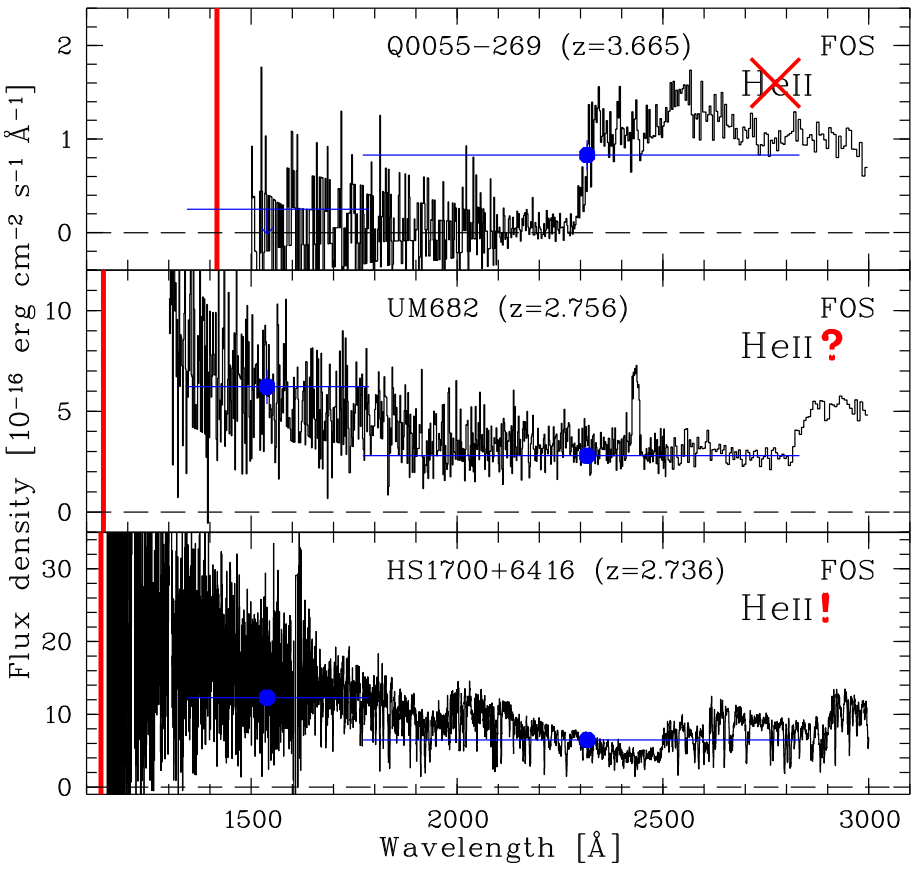
Our GALEX color selection technique

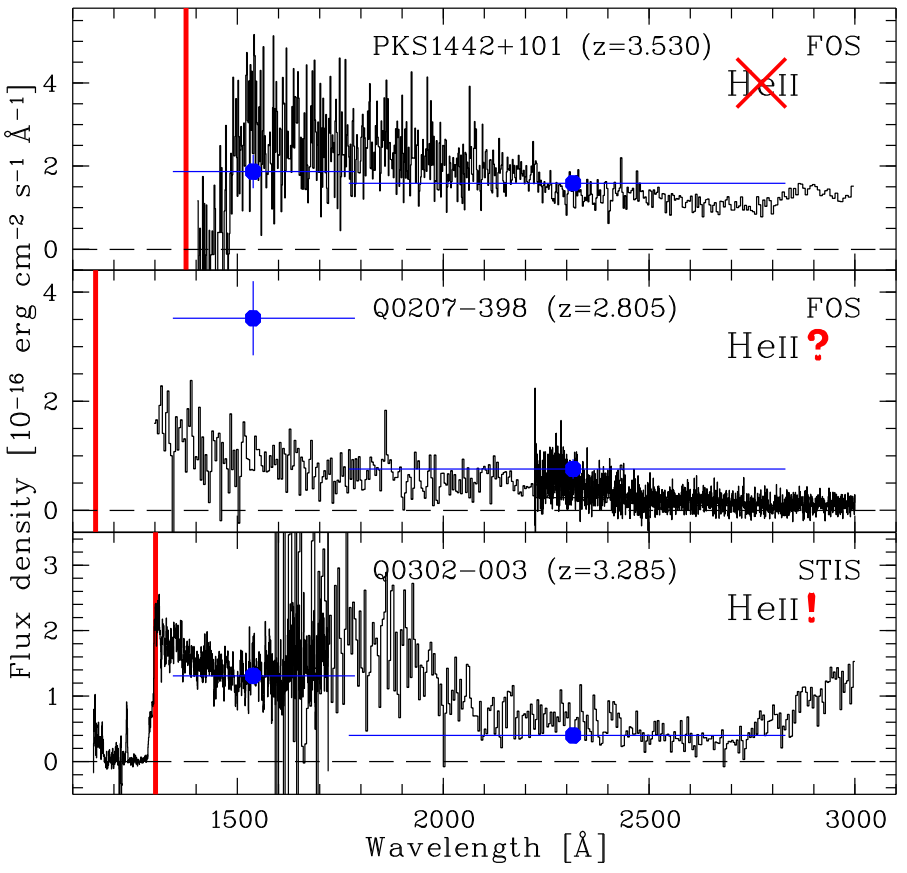
- NUV flux is not sufficient (low-z Lyman limit systems)
- significant FUV flux required (at least for $z_{em} < 3.5$ QSOs)



GALEX finds the known needles in the haystack

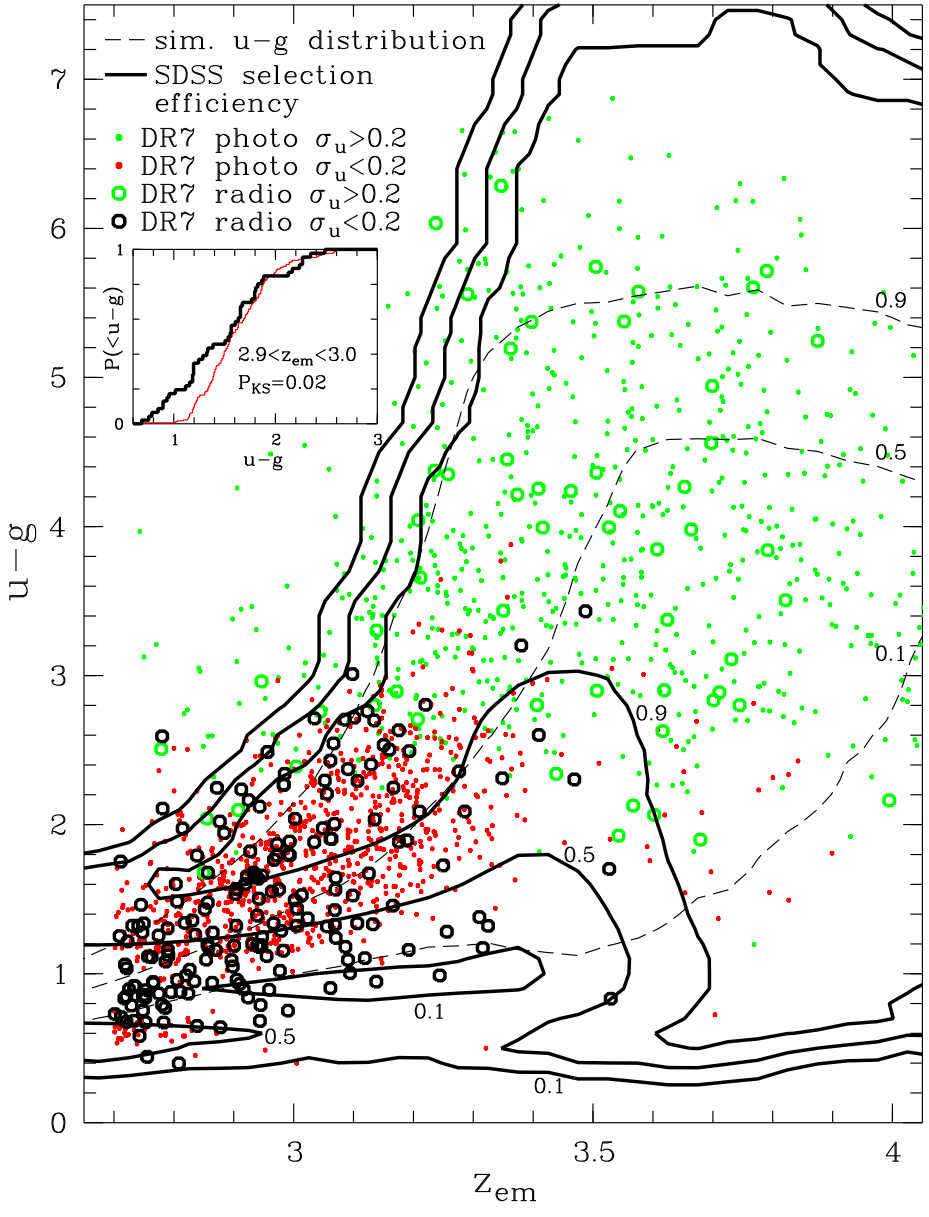
- FUV dropout: opaque sightline, He II not observable
- known He II quasars have blue GALEX UV colors





SDSS quasar selection depends on the $u - g$ color

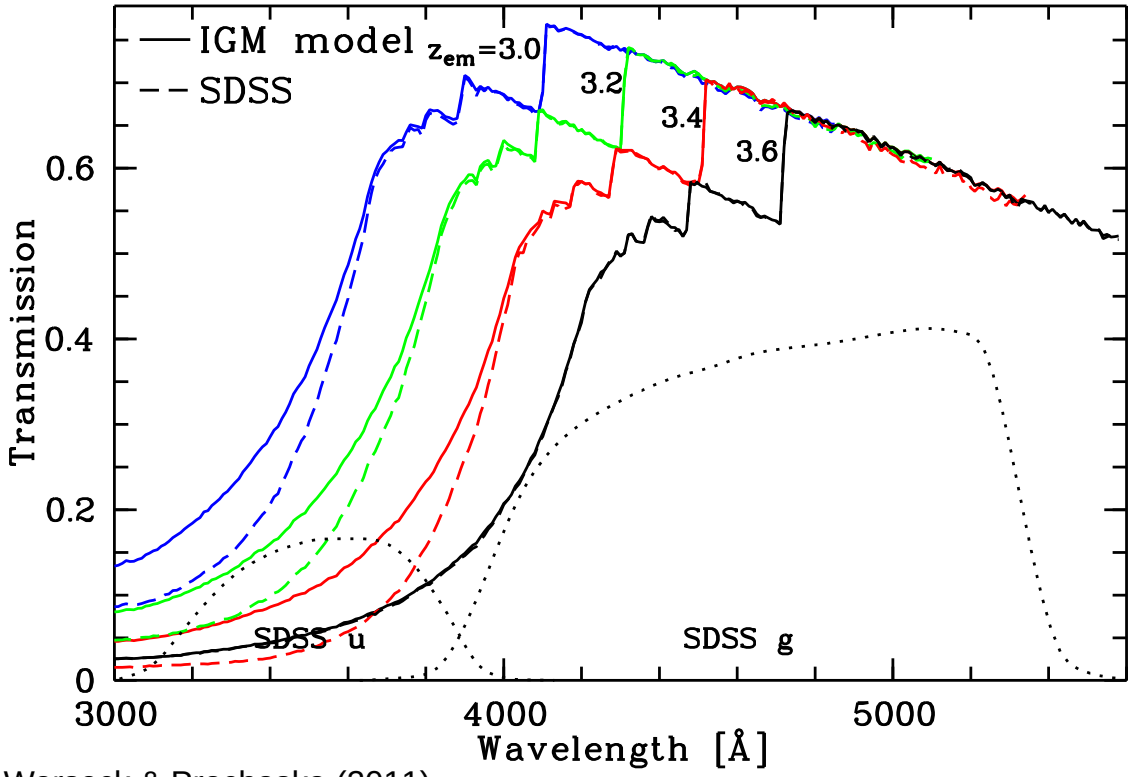
- mock SDSS photometry processed with SDSS quasar target selection routine
- color-selected SDSS quasars have redder $u - g$ colors than radio-selected quasars
- SDSS preferentially selects quasars with red $u - g$ colors at $3 < z_{\rm em} < 3.6$
- reason: red quasars are stellar locus outliers, blue quasars have colors similar to stars
  $\longrightarrow$ lost in stellar locus



Worseck & Prochaska (2011)

SDSS color bias $\longrightarrow$ SDSS Lyman limit system bias

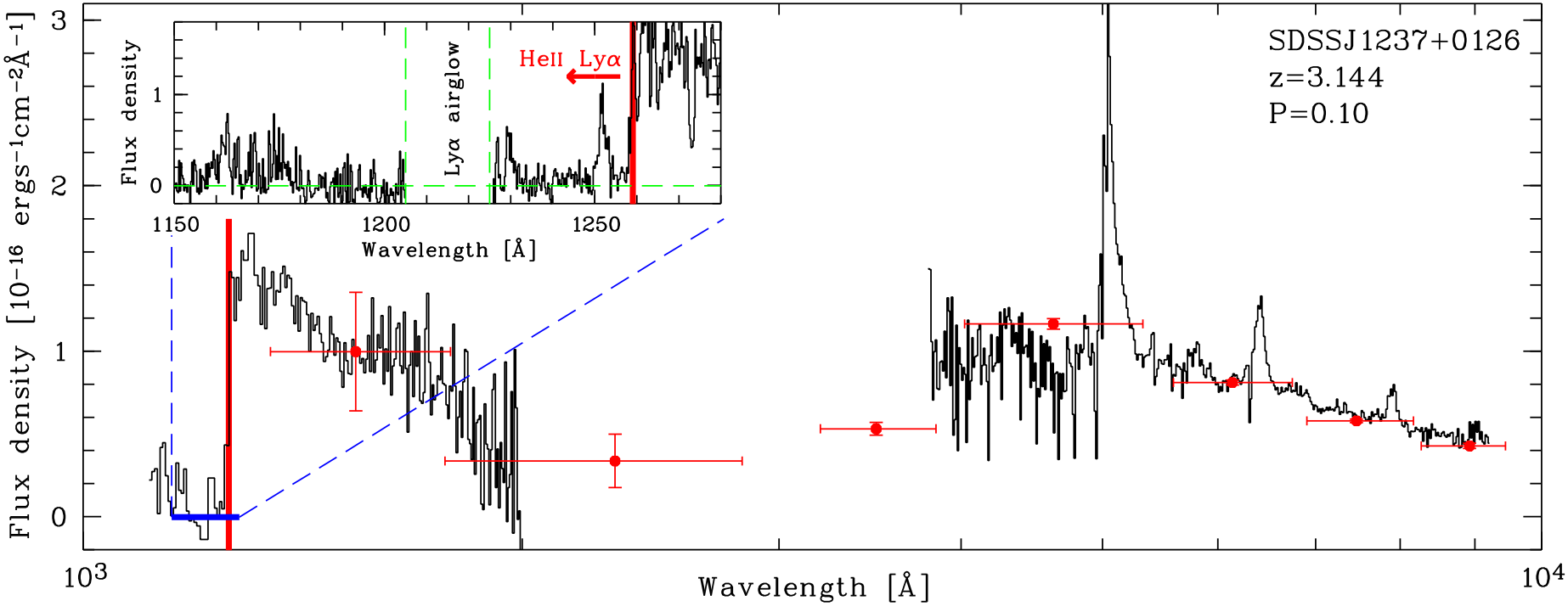
- red $u - g$ colors primarily caused by IGM Lyman continuum absorption
- SDSS is Lyman break survey at $3 < z_{\rm em} < 3.6$
- SDSS sightlines at $3 < z_{\rm em} < 3.6$ have too many Lyman limit systems
- SDSS is inefficient in finding UV-bright quasars



Worseck & Prochaska (2011)

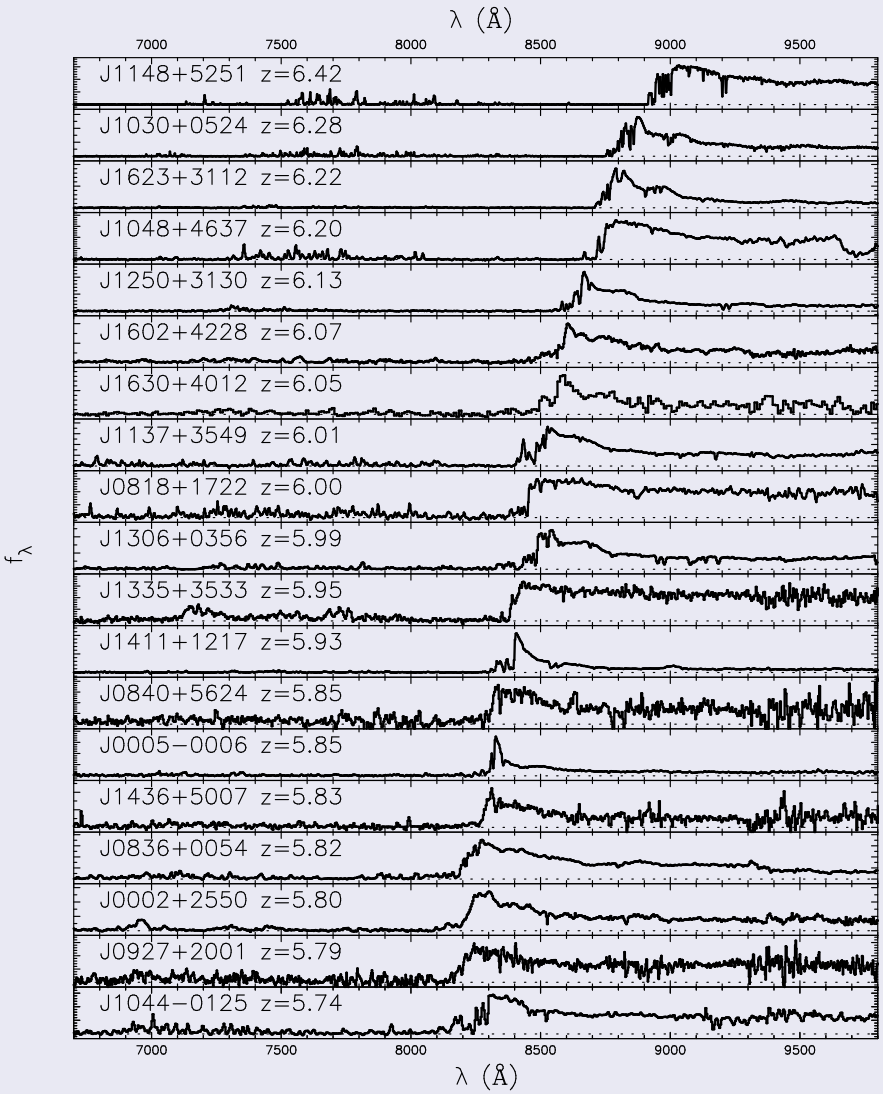
Our successful HST/COS He II survey

- GALEX color selection: predicted success rate $\sim 60\%$
- HST/COS FUV spectroscopy of 8 FUV-bright QSOs (21 orbits)
- UV-bright QSOs ($m_{\mathrm{FUV}} < 21.5$): simultaneous confirmation and follow-up
- 6/8 sightlines transparent at He II edge



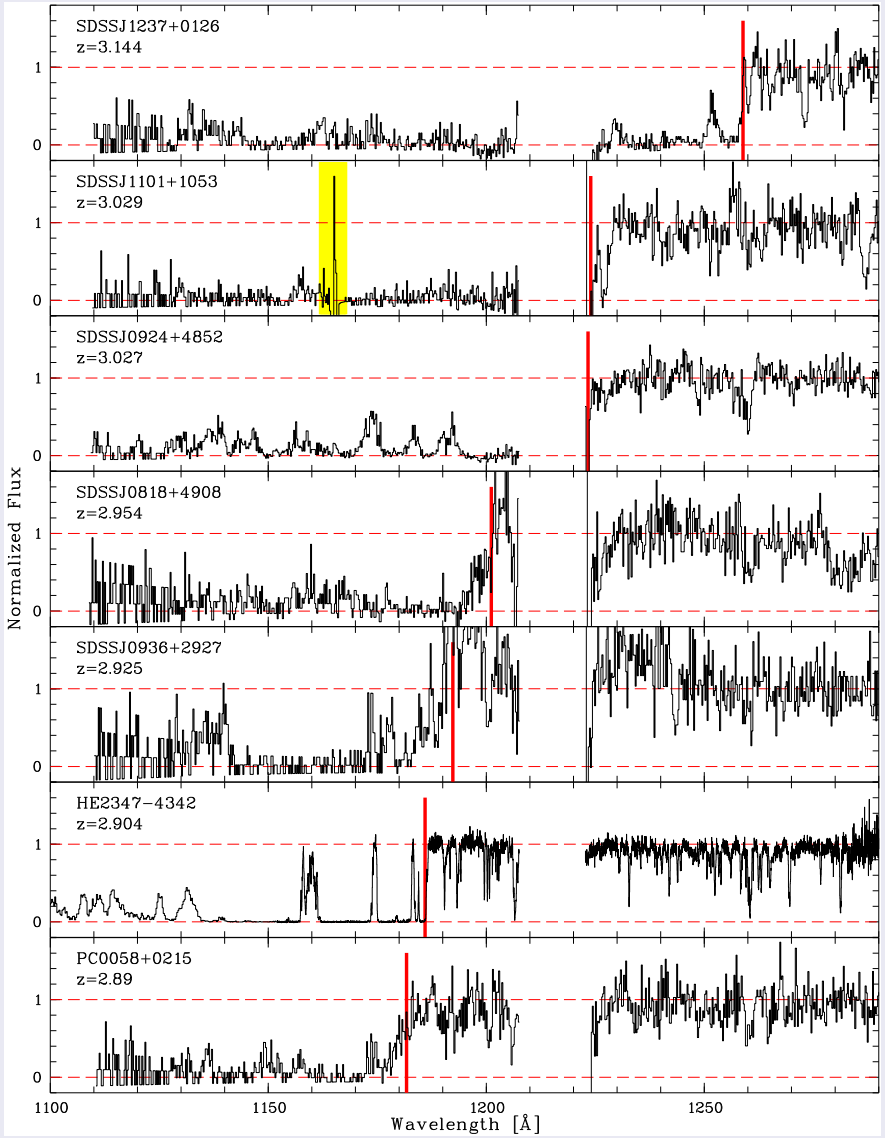
Fluctuating Gunn-Peterson troughs

Ground: Hydrogen at $z \sim 6$



Fan et al. (2006)

Far UV: Helium (He II) at $z \sim 3$



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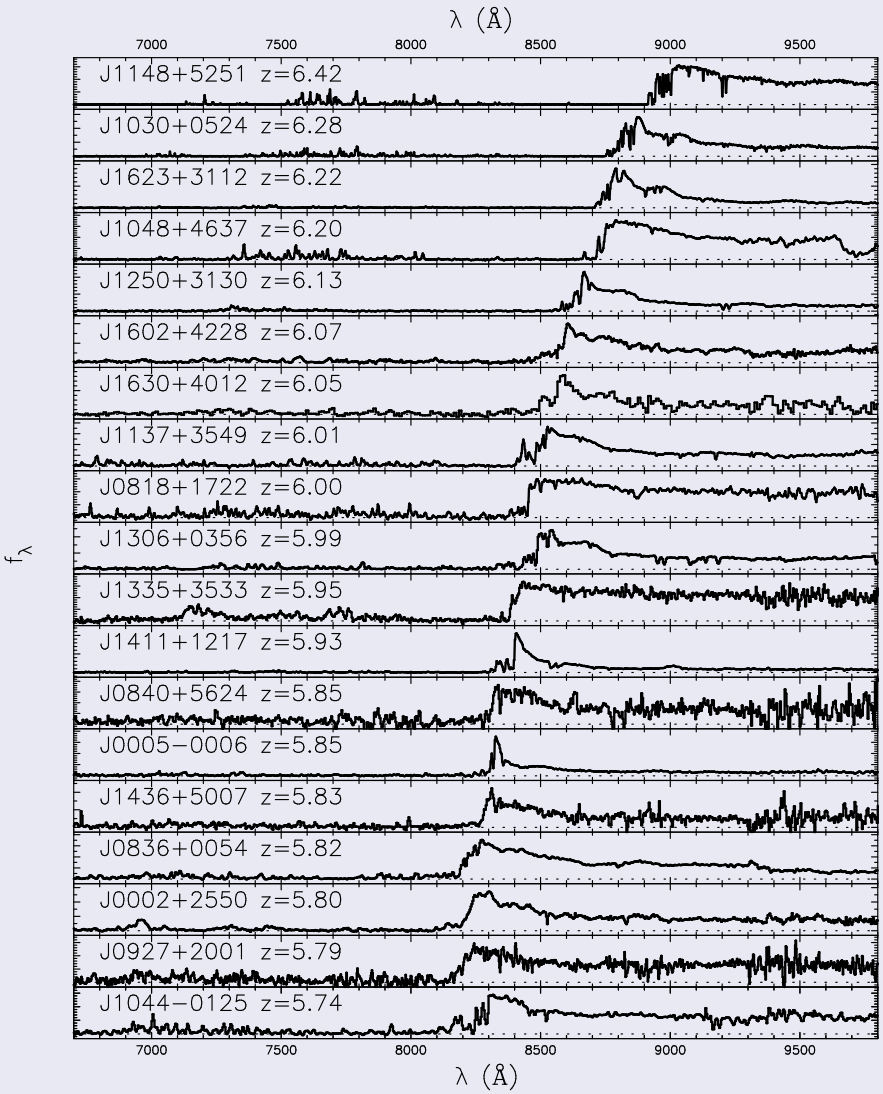

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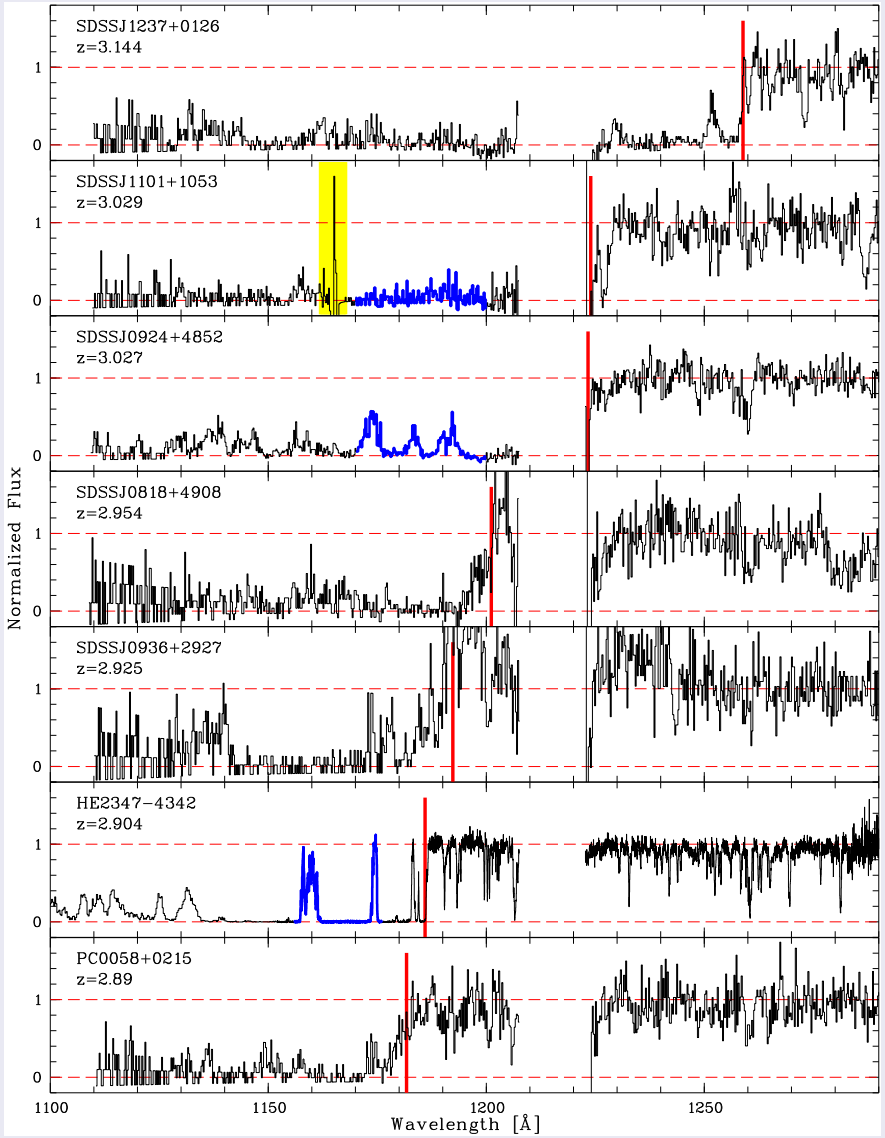
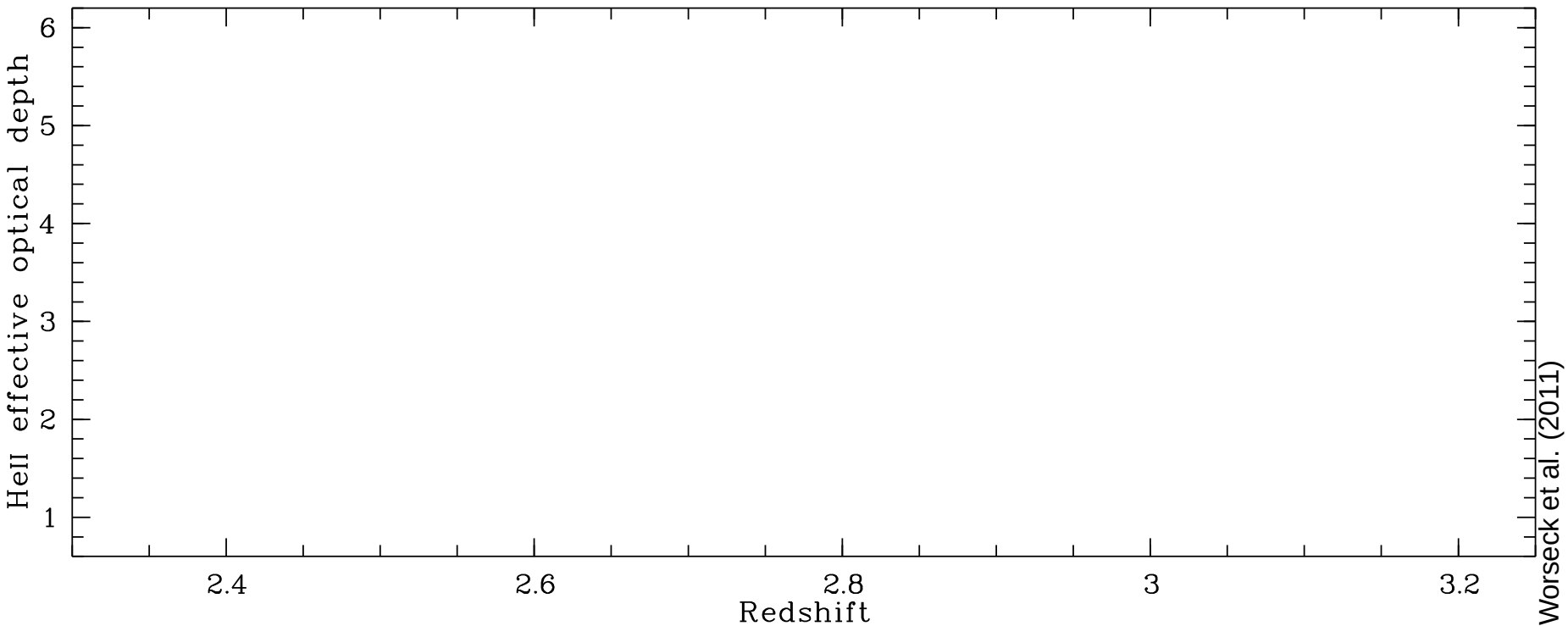


Worseck et al. (2011)

He II reionization ends at $z_{reion} \simeq 2.7$

- Measurements: He II effective optical depth on ~ 10 proper Mpc



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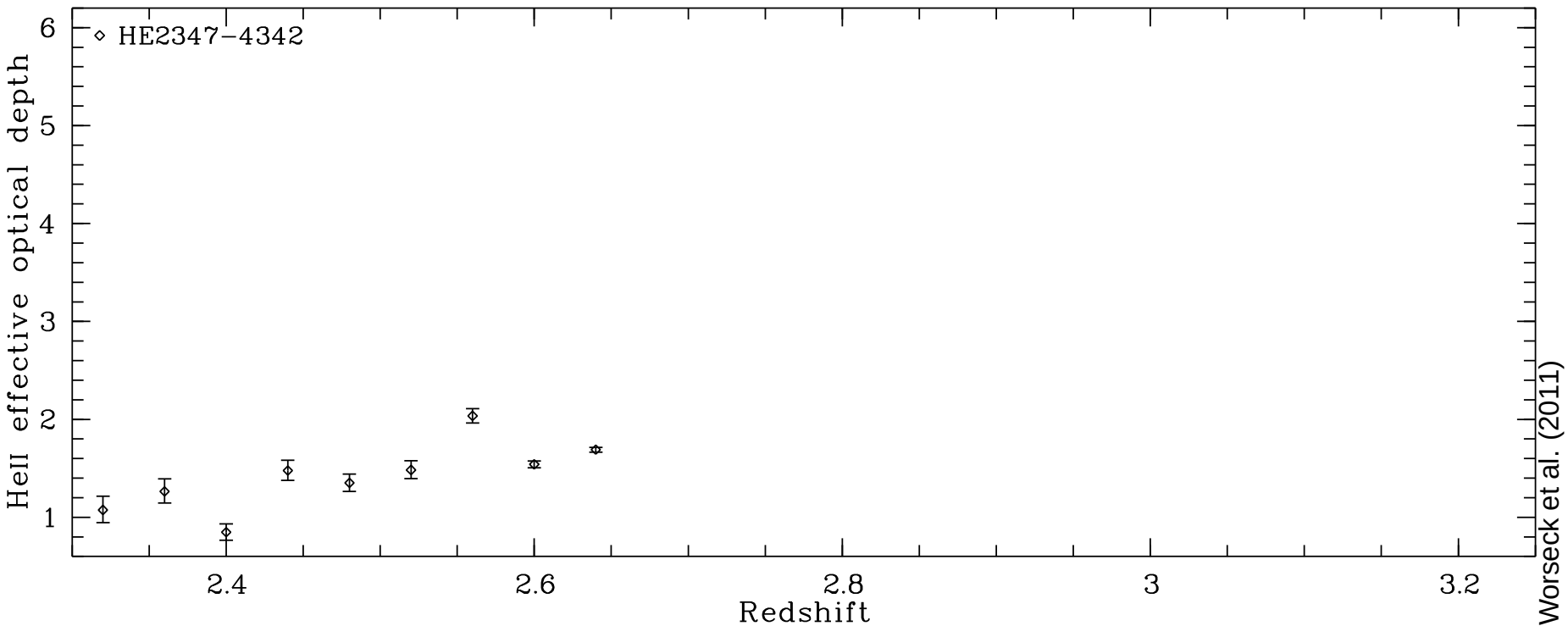

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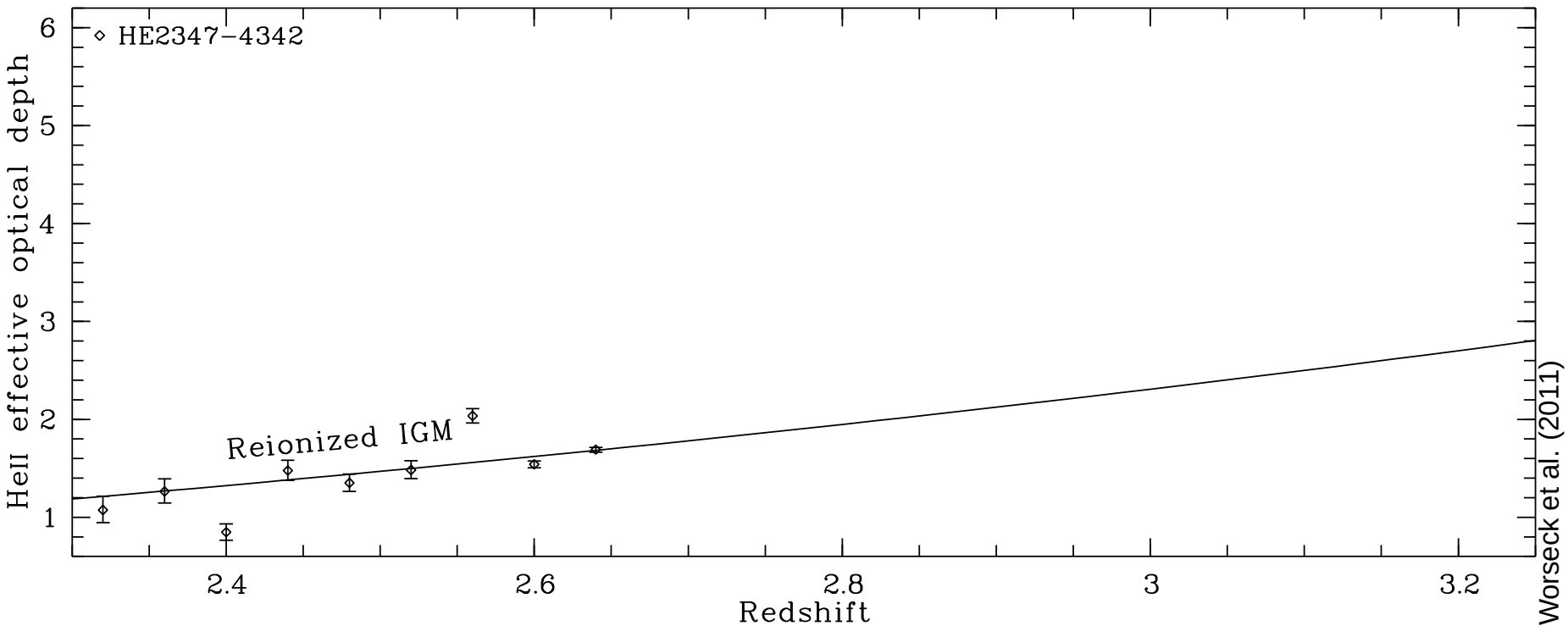

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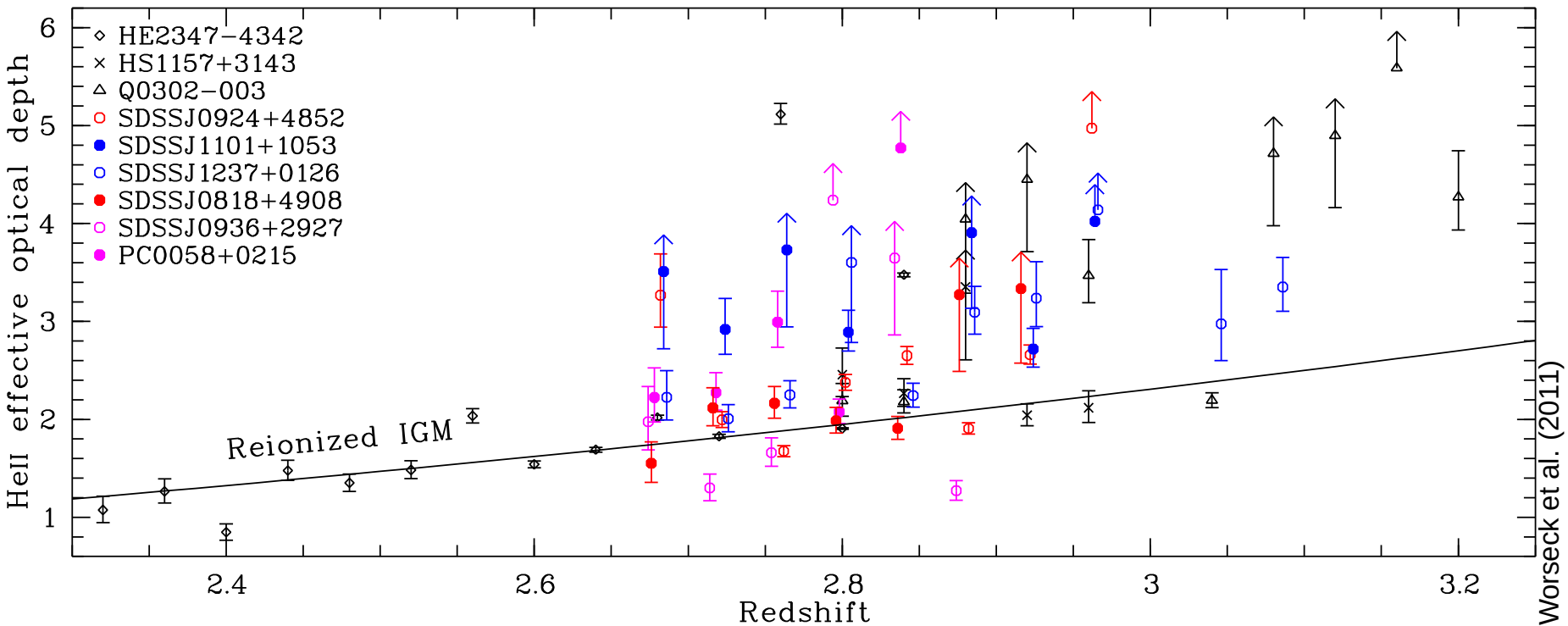
- $z \gtrsim 2.7$: large scatter in effective optical depth
- Our survey: $4\times$ redshift pathlength at $2.7 < z < 3$



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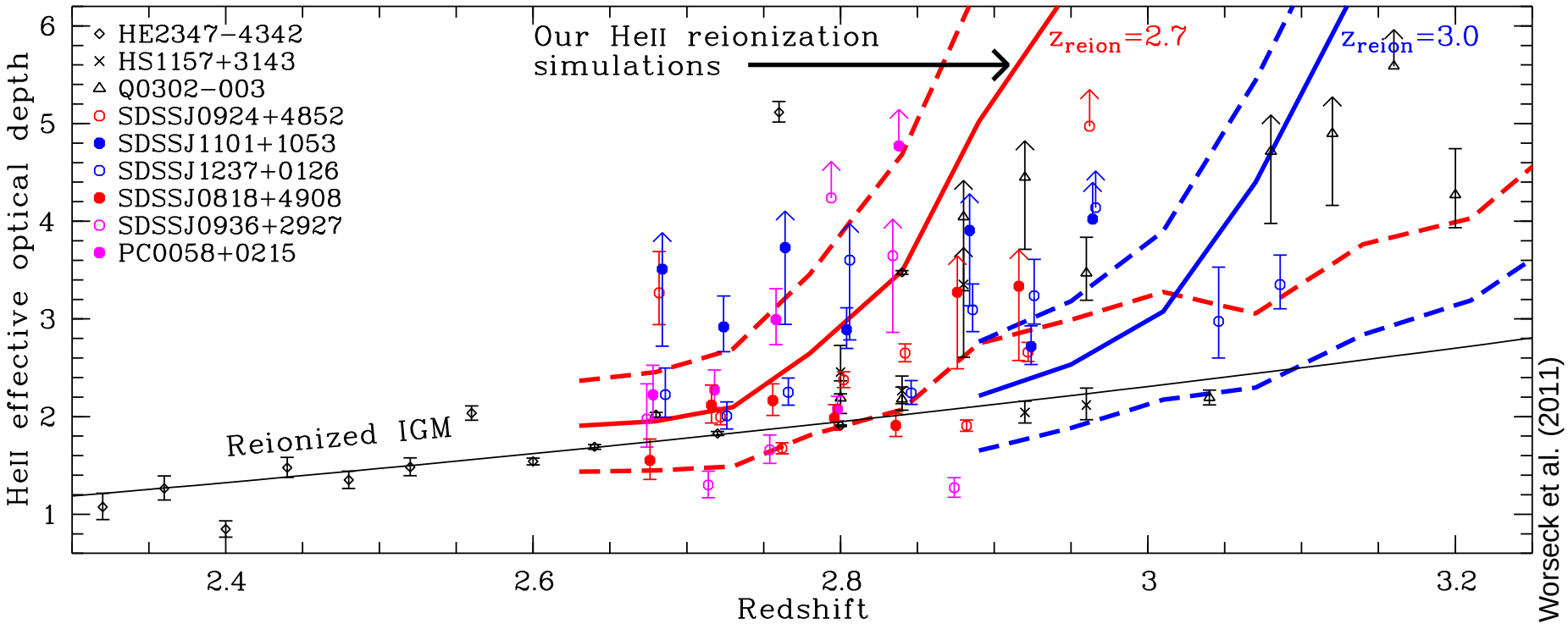
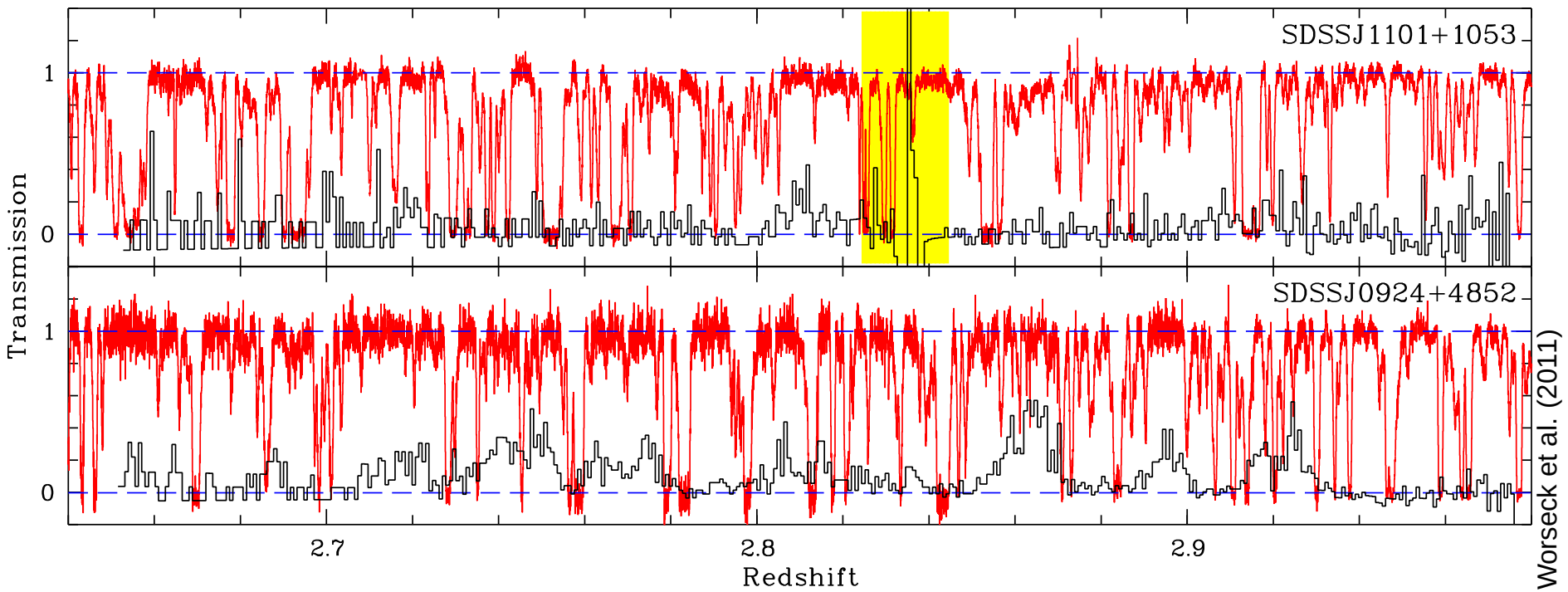
- Our survey: $4\times$ redshift pathlength at $2.7 < z < 3$
- Numerical simulations (McQuinn et al. 2009):
  good match to data for $z_{reion} \simeq 2.7$, $z_{reion} \gtrsim 3$ ruled out



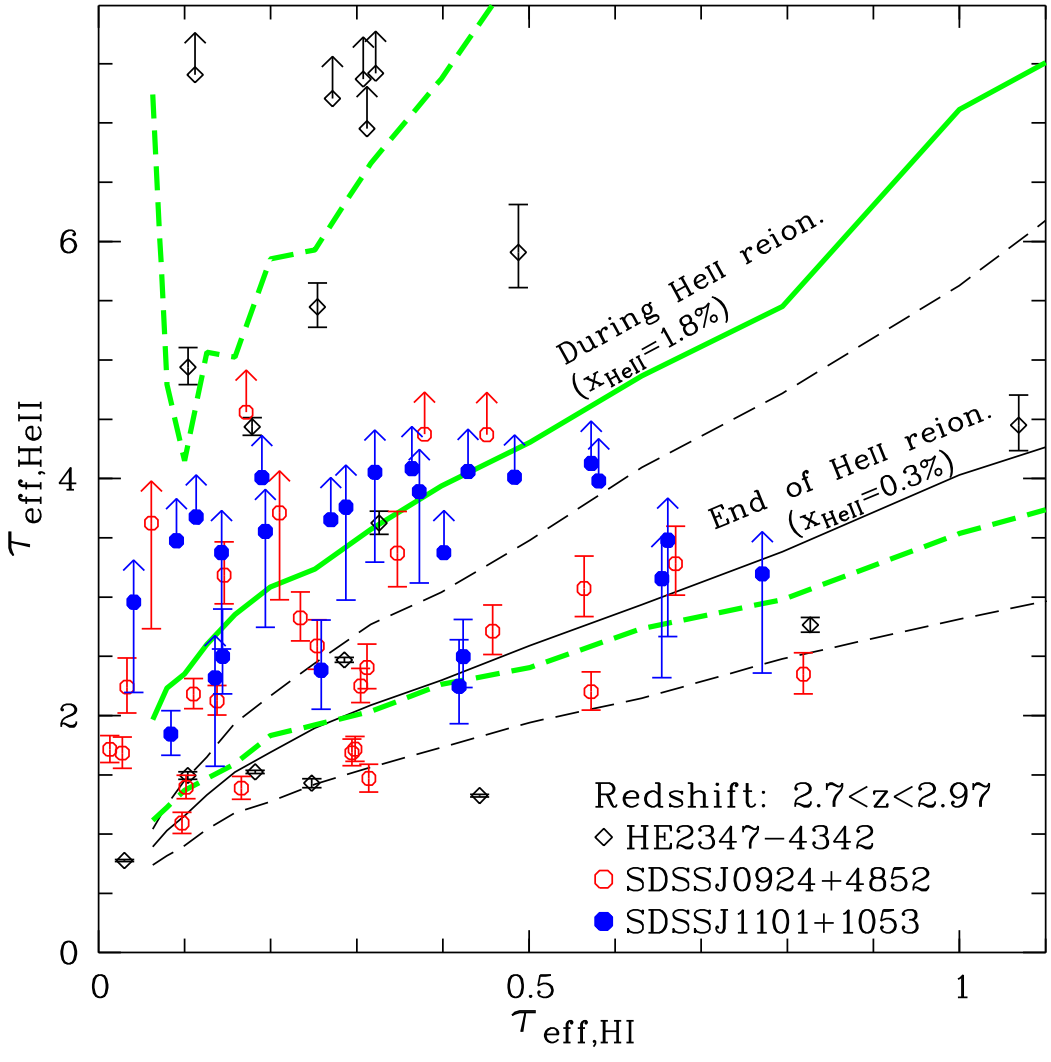
Comparison H I and He II

- H I: complementary optical spectroscopy (Keck/HIRES and VLT/UVES)
- co-eval H I Lyα forest traces density field
- underdense regions constrain He II fraction (McQuinn 2009)
- He II/H I traces SED of ionizing radiation field



The end stages of He II reionization

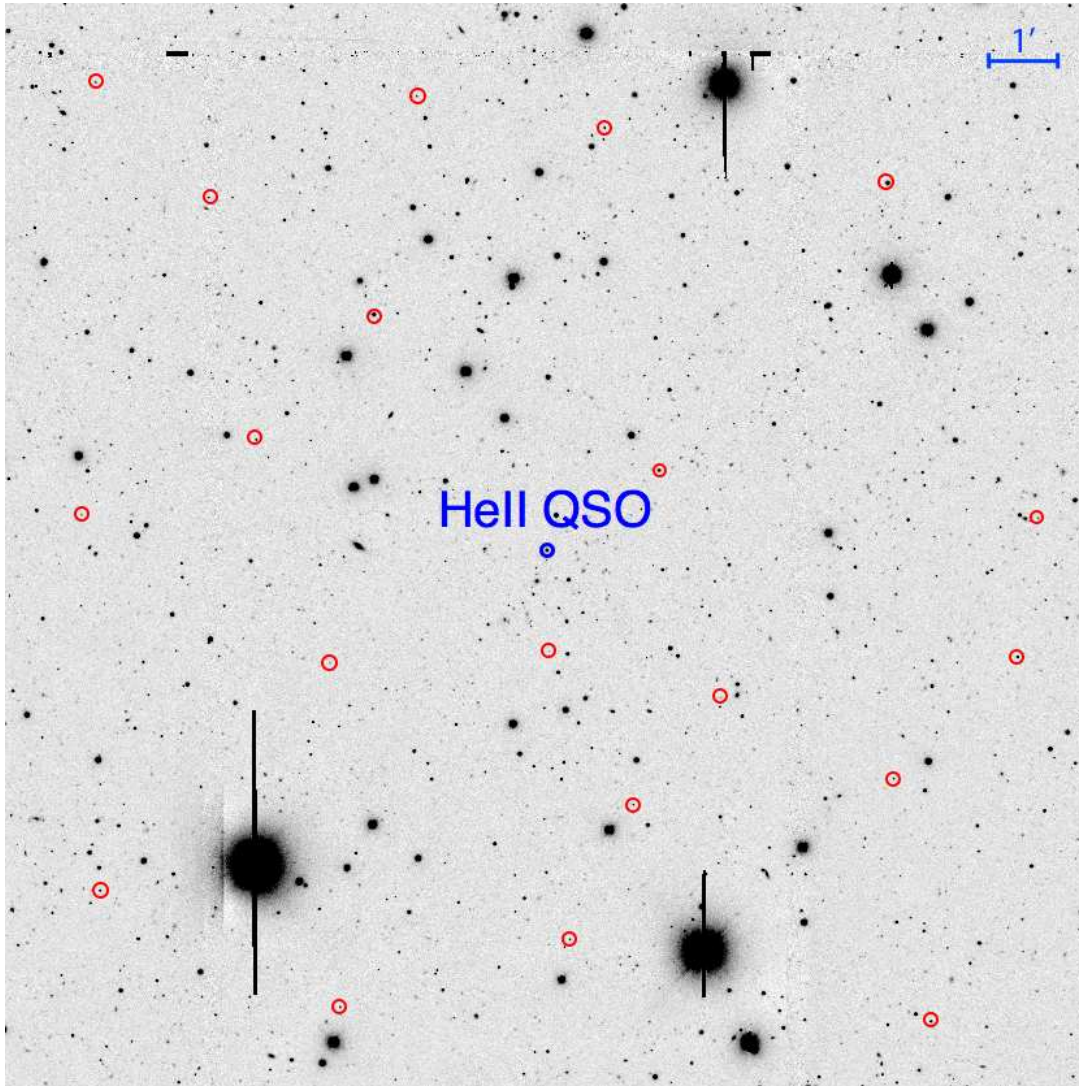
- H I breaks density degeneracy
- patchy He II absorption due to different ionization conditions instead of density fluctuations
- simulations: H I and He II correlated in reionized regions
- end stages of He II reionization at $2.7 < z < 3$



Worseck et al. (2011)

A dedicated survey for He II-reionizing quasars

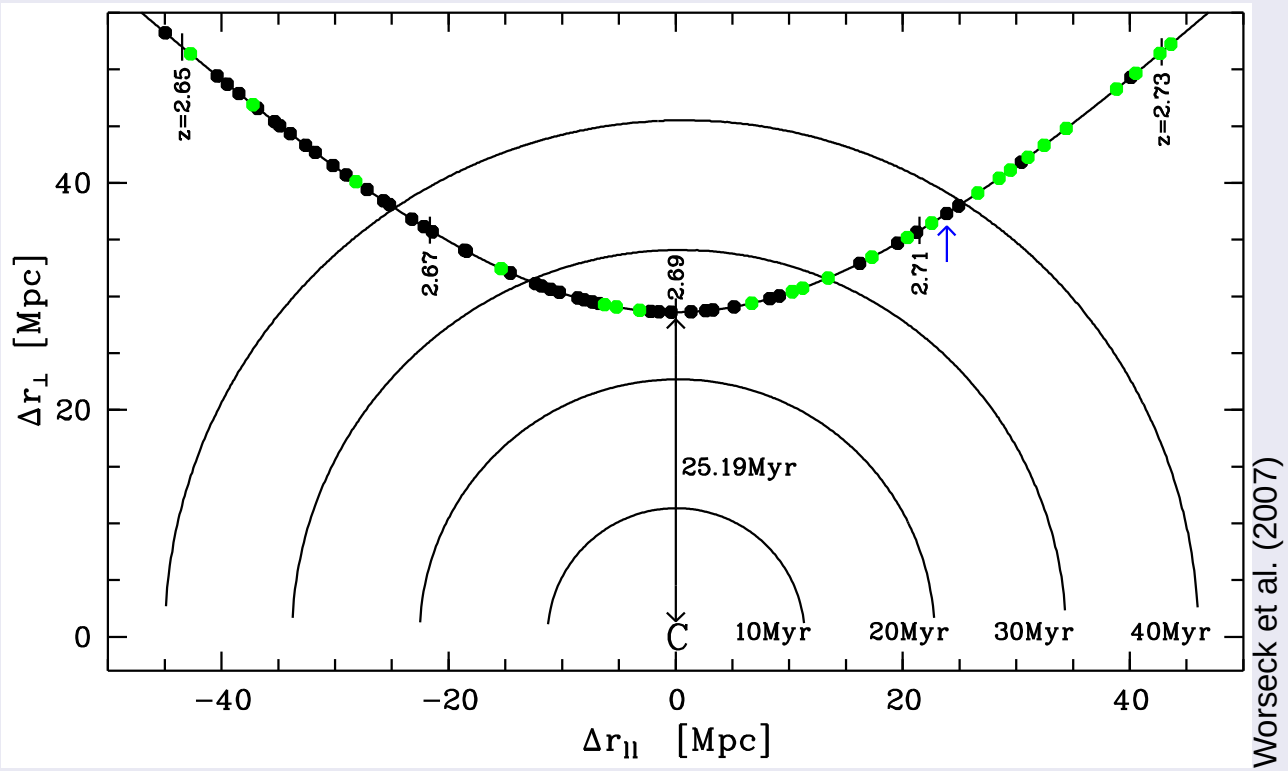
- Lyman break survey for faint ($g \lesssim 24.5$) quasars in the vicinity of He II sightlines
- goal: associate quasars with He II absorption features
- wide field ($30' \times 30'$) deep u band imaging
  - LBC @ LBT
  - MOSAIC @ KPNO
- spectroscopic follow-up
  - VIMOS @ VLT
  - LRIS @ Keck



Goal: Constrain quasar lifetime and anisotropy

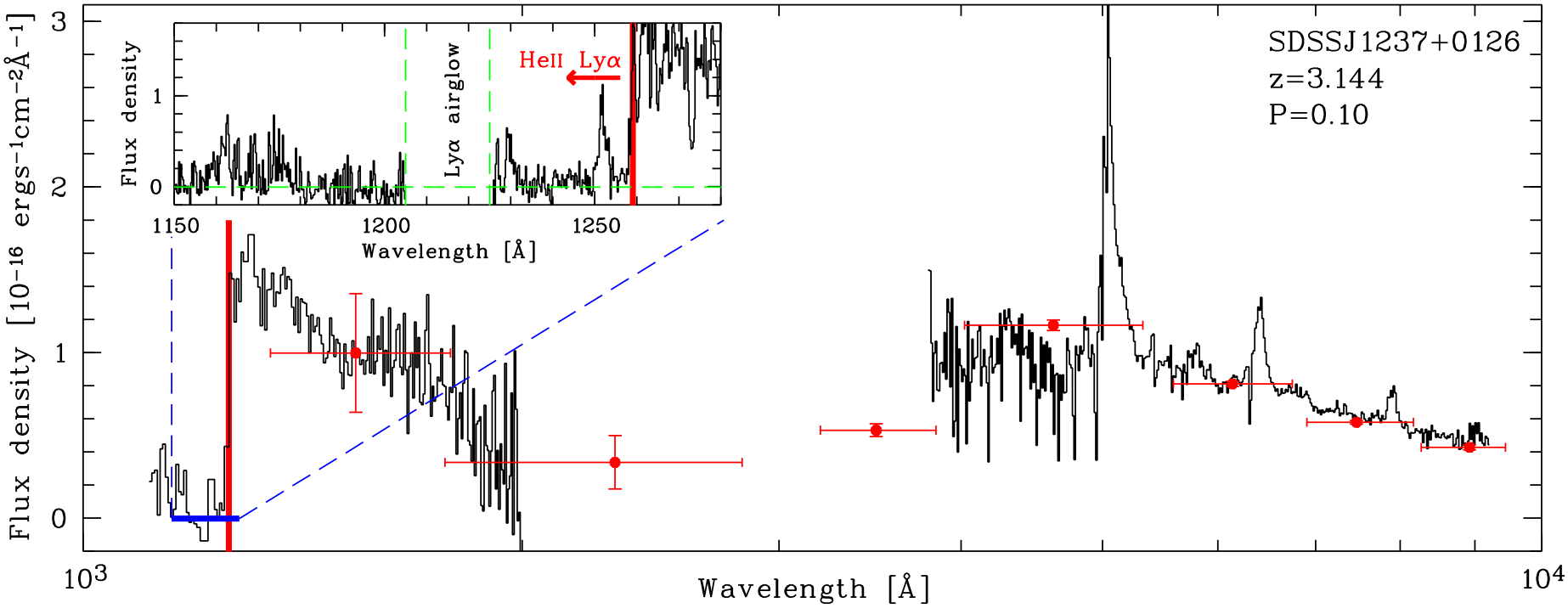
- He III zone or hard UV radiation near foreground quasar
  $\longrightarrow$ light travel time gives lower limit on quasar lifetime
- current sample (3 quasars): 10–30 Myr

Quasar light fronts in comoving space



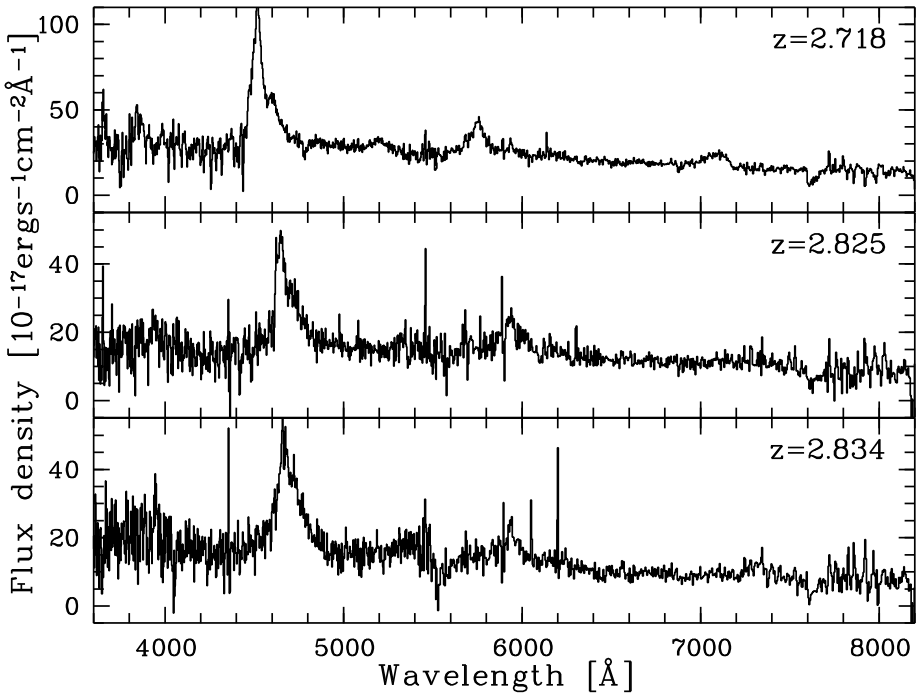
A dedicated multi-color survey for UV-bright quasars

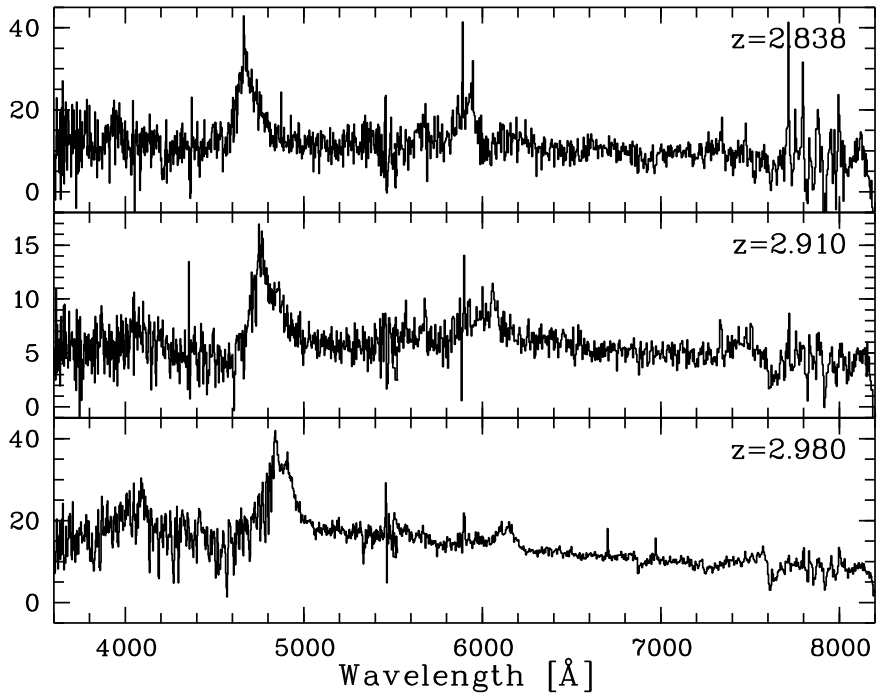
- most GALEX-detected quasars too faint for HST
- SDSS selects against UV-bright quasars
- goal: find the missing quasars via their unusual SED



Intitial results: 22 UV-bright $z > 2.7$ quasars

- follow-up spectroscopy of promising SDSS+GALEX sources with Lick/KAST and CAHA/CAFOS
- so far: 22 quasars ($2.7 < z < 3.8$) ready for HST/COS
- continuation in 2012





Shedding light on the 2nd epoch of reionization

- He II Lyα absorption probes He II reionization
  - Gunn-Peterson troughs $\longrightarrow$ large He II fraction
  - Large sample variance predicted $\longrightarrow$ large samples required
- Efficient He II target selection via GALEX photometry
  - Blue GALEX colors indicate transparent sightlines
  - SDSS selects against UV-bright quasars
- HST/COS: Six new He II absorption spectra
  - $4\times$ previous redshift pathlength in He II absorption
  - Variance in He II absorption at $z \sim 2.9$
    $\longrightarrow$delayed and inhomogeneous He reionization
  - Comparison to simulations: He II reionization ended at $z \simeq 2.7$
- Resolving the process of He II reionization
  - New sample of UV-bright quasars missed by SDSS
  - Survey for foreground quasars to interpret He II absorption spectra
  - Unique constraints on quasar lifetime and anisotropy